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2308M13C

MEMORANDUM FOR PR (In-House Contractor/In-House Publication)
FROM: PROI (TI) (STINFO) 29 February 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-038**
Chchroudi, B. (ERC), Badakshan, A., Cohn, R., Talley, D., "Injection of Cryogenic Fluids into Subcritical and Supercritical Environments"
Invited University Seminar **(Statement A)**
Eidgenossische Technische Hochschule (ETH), Zurich, Switzerland
17 Mar 2000 **(Absolute Deadline: 09 Mar 2000)**

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
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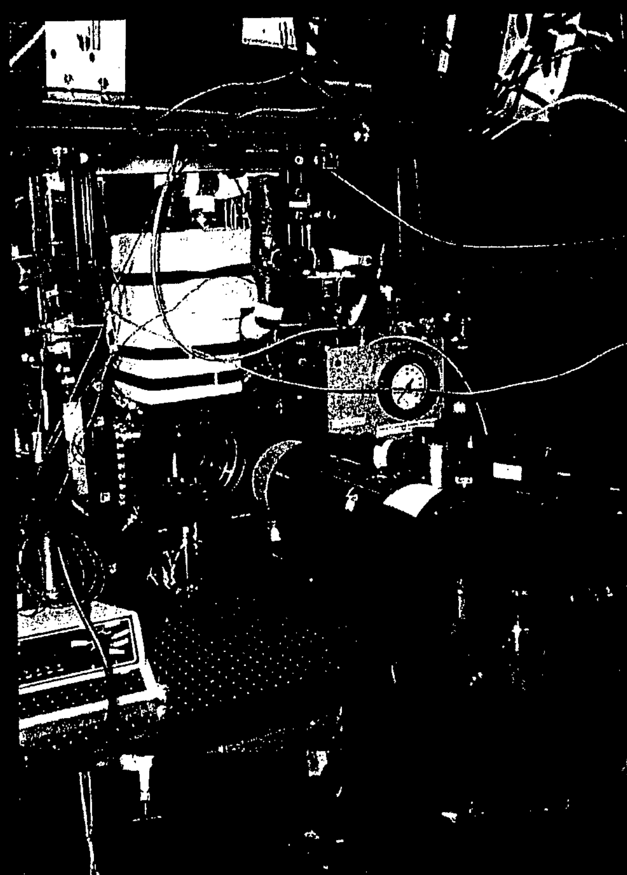
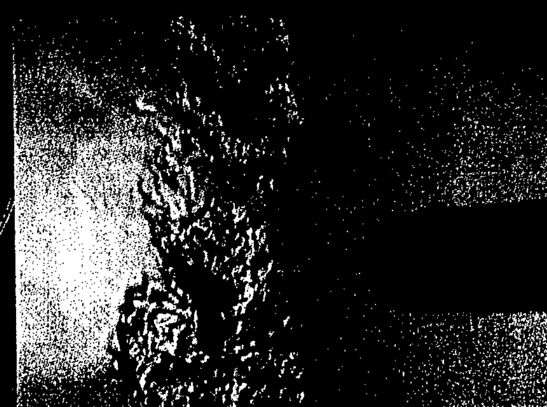
ROBERT C. CORLEY (Date)
Senior Scientist (Propulsion)
Propulsion Directorate

Injection of Cryogenic Fluids into Subcritical and Supercritical Environments



Doug Talley
Group Leader, Rocket Combustion Devices
Air Force Research Laboratory



Credits

Principle Investigators

- Dr. Bruce Chehroudi
- Dr. Roger Woodward

Collaborators

- R. Cohn
- E. Coy
- A. Badakshan
- D. Poulikakos

Motivation

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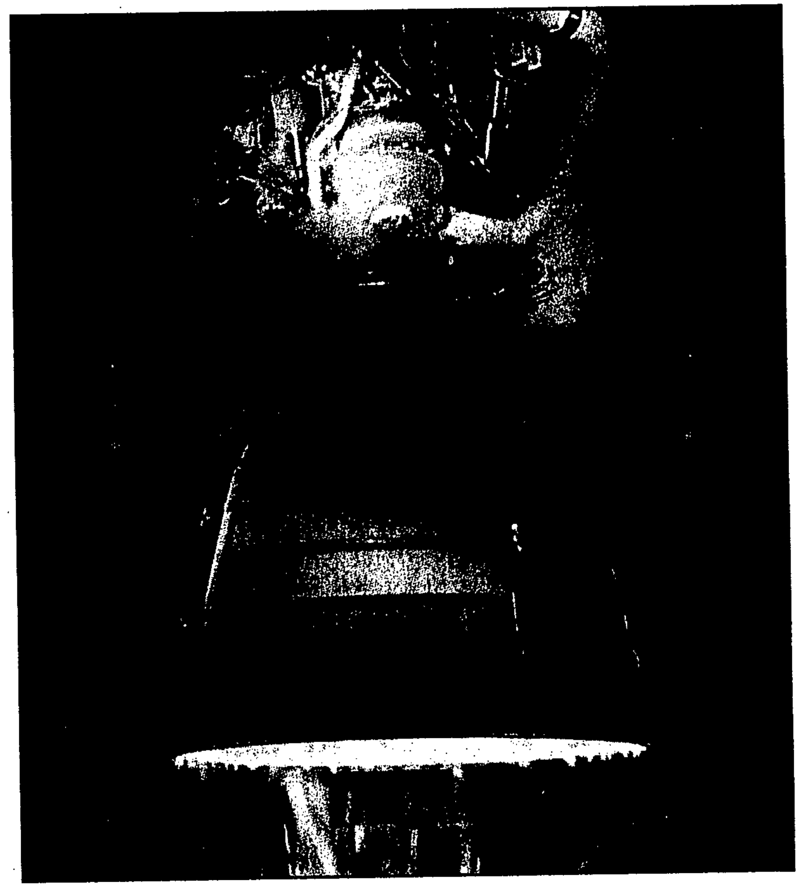
At Edwards

- Supercritical conditions that can exist inside rocket engines

Other

- Gas turbines
- Diesel
- etc



Space Shuttle Main Engine
LOX/H2, 500,000 lb thrust (112,000 N)

The Problem

- It is often advantageous to operate combustion chambers at pressures exceeding the critical pressure of one or both propellants.
  - Higher chamber pressures lead to greater performance (Isp).
- At supercritical pressures, the distinct difference between gas and liquid phases disappears.
  - Conventional "spray combustion" experience no longer applies.
- It is not known how to replace conventional "spray combustion" models in engine design codes.
  - *The lack of understanding leads to potentially large engine design errors.*

The Problem (3)

Other factors not normally considered in conventional spray combustion

- Vanishing surface tension and enthalpy of vaporization.
- Equivalent “gas” and “liquid” phase densities.
- Strongly enhanced solubility of one species (“gas”) into another (“liquid”).
- Reduced gas phase diffusivity (more liquid-like).
- Large property excursions near the critical point
  - Conductivity, viscosity, speed of sound, specific heats.
- Mixing induced critical point variations.
- Enhanced gas phase unsteadiness.
- Potentially different kinetics mechanisms.

Objectives

Determine the mechanisms which control the breakup, transport, mixing, and combustion of subcritical and supercritical droplets, jets, and sprays.

Experimental Set-up

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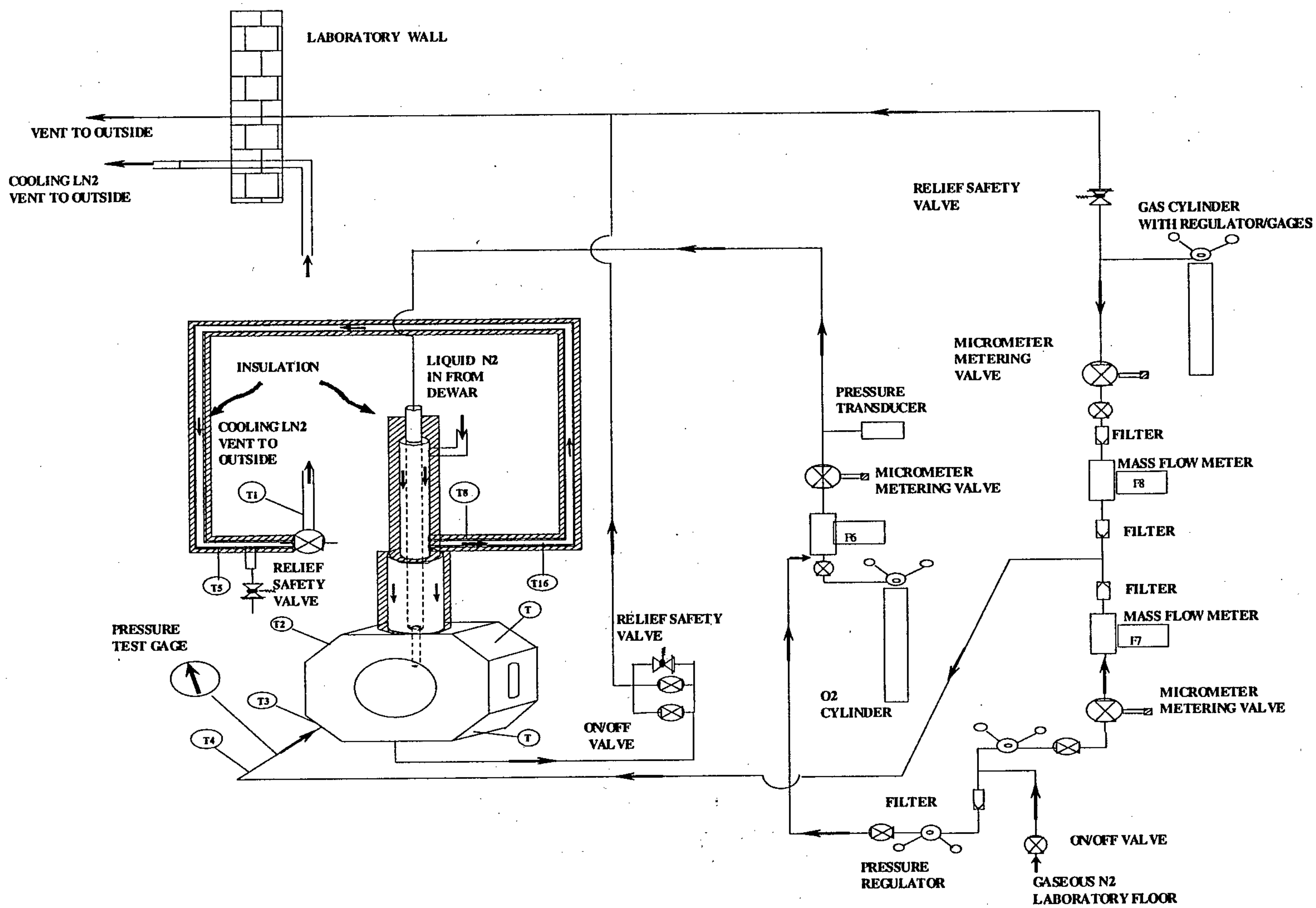

Transcritical LOX drops in room temperature GN2

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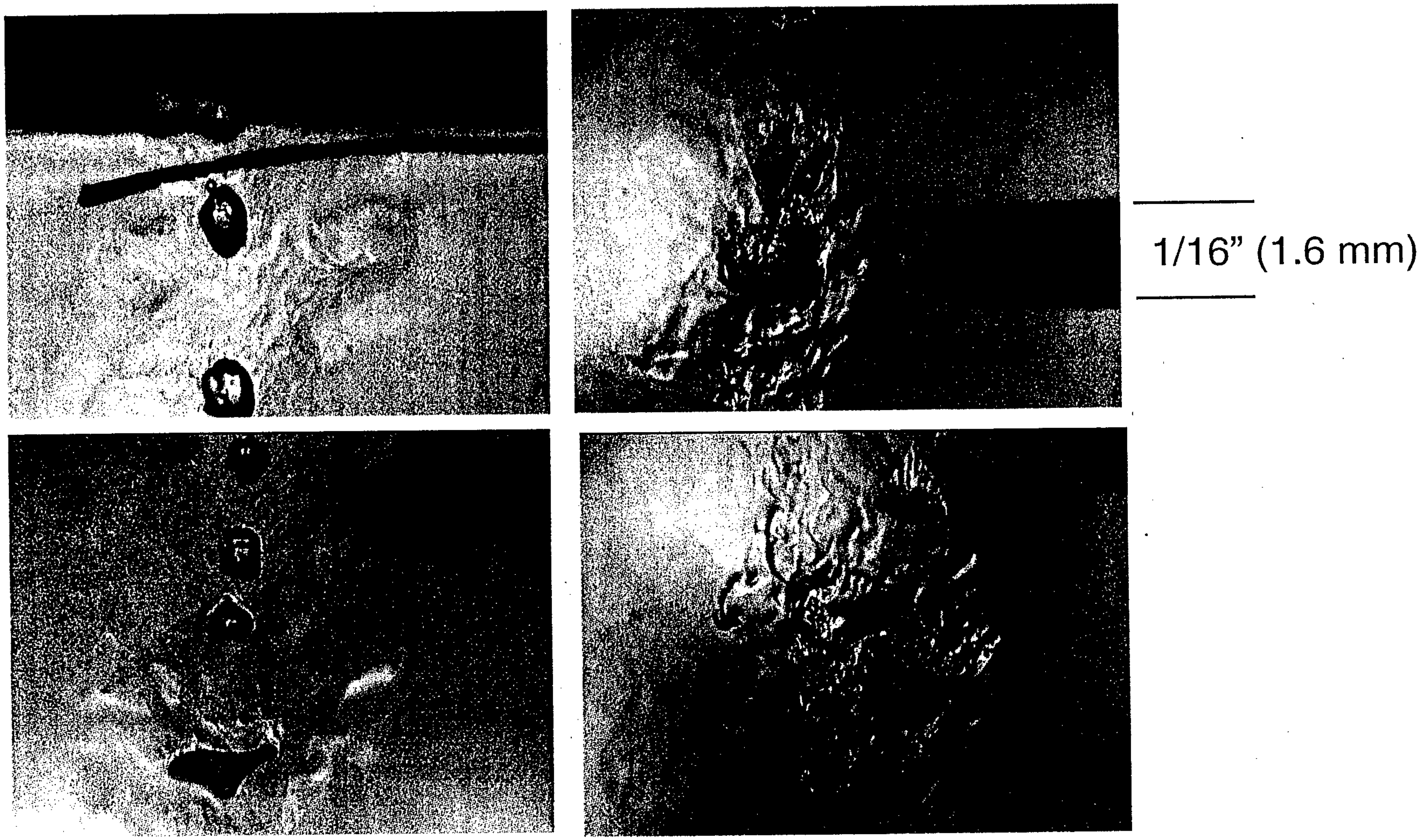

Representative evolution of transcritical drop disintegration

Transcritical LOX drops in room temperature GN2 (2)

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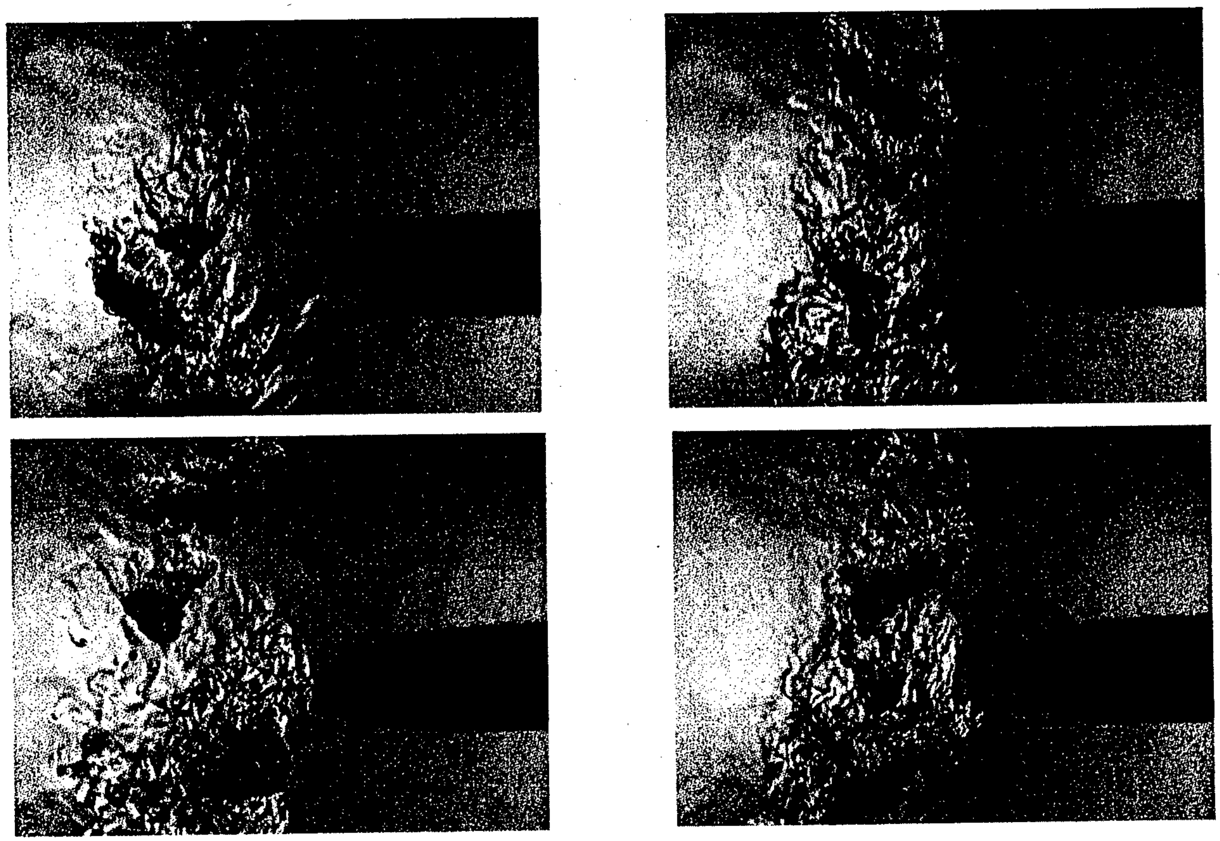
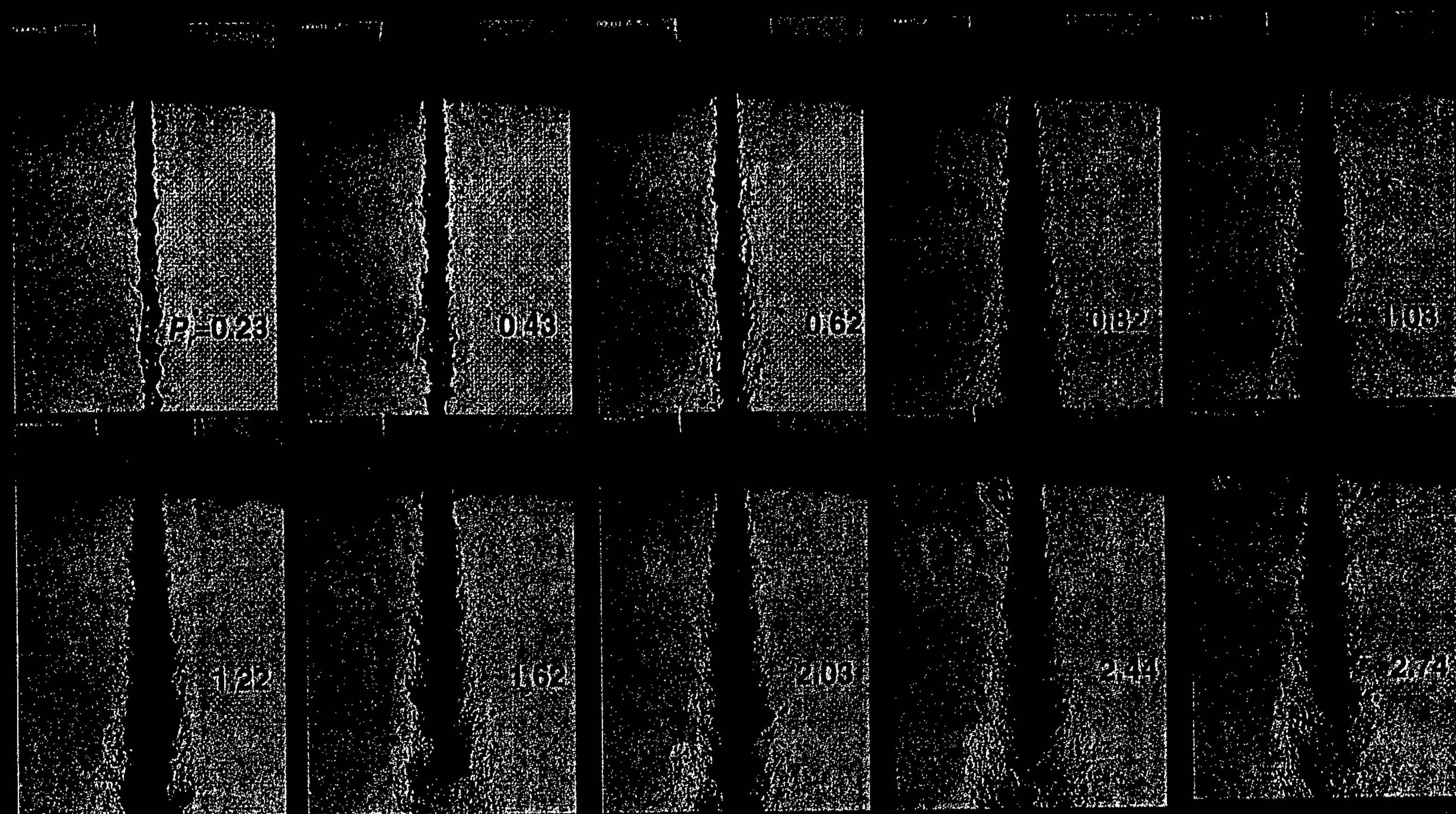


Visualization at different times at the same location

Shadowgraph Results - N_2 into N_2

$P_{cr} = 3.39$ MPa $T_{amb} = 300$ K   Re = 25,000- 75,000

$T_{cr} = 126$ K $T_{inj} = 99\text{-}120$ K $V_{inj} = 10\text{-}15$ m/s



Mixing Layer Structure - N_2 into N_2

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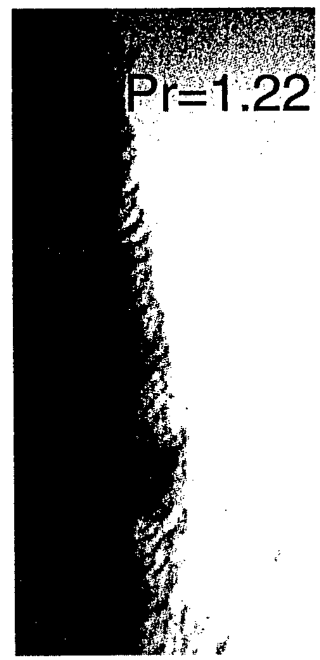
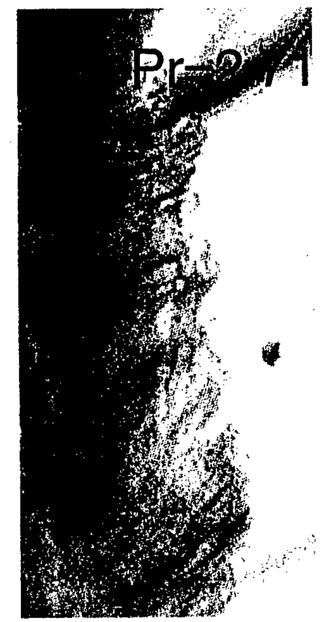
$P_{cr} = 3.39$ Mpa, $T_{cr} = 126$ K, $T_{inj} = 128$ K, $T_{amb} = 300$ K

Low Pres.
Subcritical
Droplets



Mod. Pres.
Supercritical
Transition



High Pres.
Supercritical
Gas layers

Jet Spreading Angles

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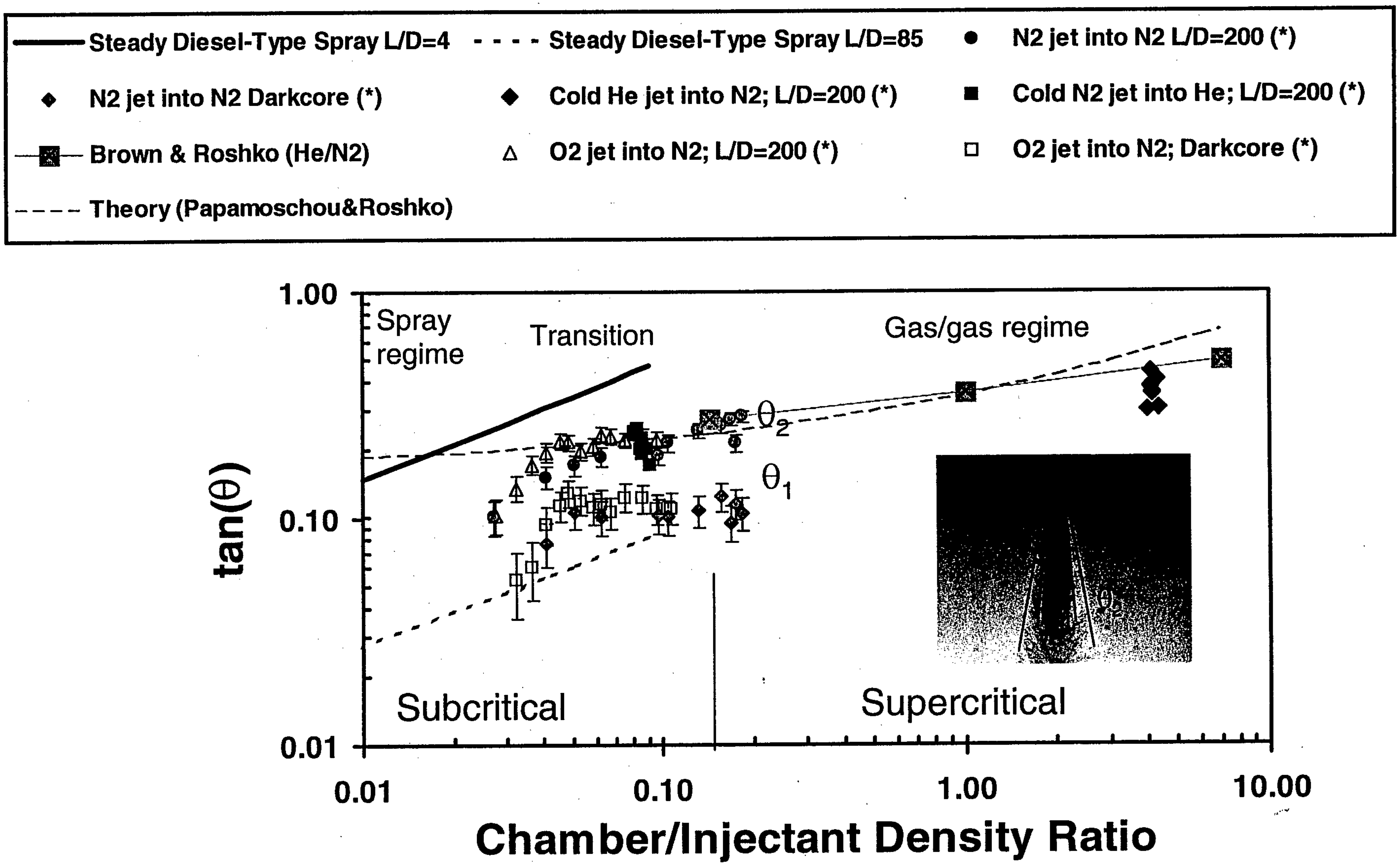
Chehroudi et. al., AIAA 99-0206, AIAA 99-2489



Characteristic Times

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- Characteristic bulge formation time (τ_b) at the jet interface (Tseng et al.): $(\rho_l L^3/\sigma)^{1/2}$; ρ_l , L, σ are liquid density, characteristic dimension of turbulent eddy, and surface tension, respectively.
- Characteristic time for gasification (τ_g) (D-square law): D^2/K; D and K are drop diameter and vaporization constant.
- A Hypothesis: If these two characteristic times (calculated for appropriate length scales) are comparable then an interface bulge may not be separated as an unattached entity (onset of the gas-jet behavior at supercritical condition)

Similar equations for different cases

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- Theoretical isothermal liquid spray growth rate (θ_s) based on Orr-Sommerfeld equation and stability analysis to find the wavelength of the most unstable interface wave:
  $\theta_s \cong 0.27\,[0 + (\rho_g/\rho_l)^{0.5}]$
- Papamoschou/Rashko theory for incompressible variable-density gaseous mixing layer/jet:
  $\theta_{P/R} \cong 0.17\,[1 + (\rho_g/\rho_l)^{0.5}]$
- Dimotakis theory for incompressible variable-density gaseous mixing layer/jet:
  $\theta_D \cong 0.212\,[0.59 + (\rho_g/\rho_l)^{0.5}]$
- ALL HAVE THE SQUARE ROOT OF DENSITY RATIO AND THE SAME EQUATION FORMAT

Empirical Correlation

- Based of the information of the previous slide the following "intuitive/smart" equation is proposed for both sub- and supercritical measured growth rates:

$$\theta_{Ch} \cong 0.27[(\tau_b/(\tau_b+\tau_g))+(\rho_g/\rho_l)^{0.5}]$$

Note:

- For isothermal liquid case: $\tau_g >> \tau_b$ and $\tau_g \rightarrow \infty$. It then collapses to the isothermal spray case.
- For subcritical the $(\tau_b/(\tau_b+\tau_g))$ is calculated until it reaches 0.5. After that it is maintained constant at 0.5 for supercritical gas-like jet. The transition point is found to be approximately when $(\tau_b/(\tau_b+\tau_g)) \cong 0.5$ (i.e. $\tau_b \cong \tau_g$).

Empirical Correlation (2)

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- $(\tau_b/(\tau_b + \tau_g))$ is assumed to be a dominant function of the density ratio (ρ_g/ρ_l); i.e. $\tau_b/(\tau_b + \tau_g)) = F(\rho_g/\rho_l)$.
- The function F is only calculated for the N2-into-N2 case and is taken to be the same for other (N_2-into-He ans N_2-into-Ar) cases. That is, for example, for N_2-into-He :

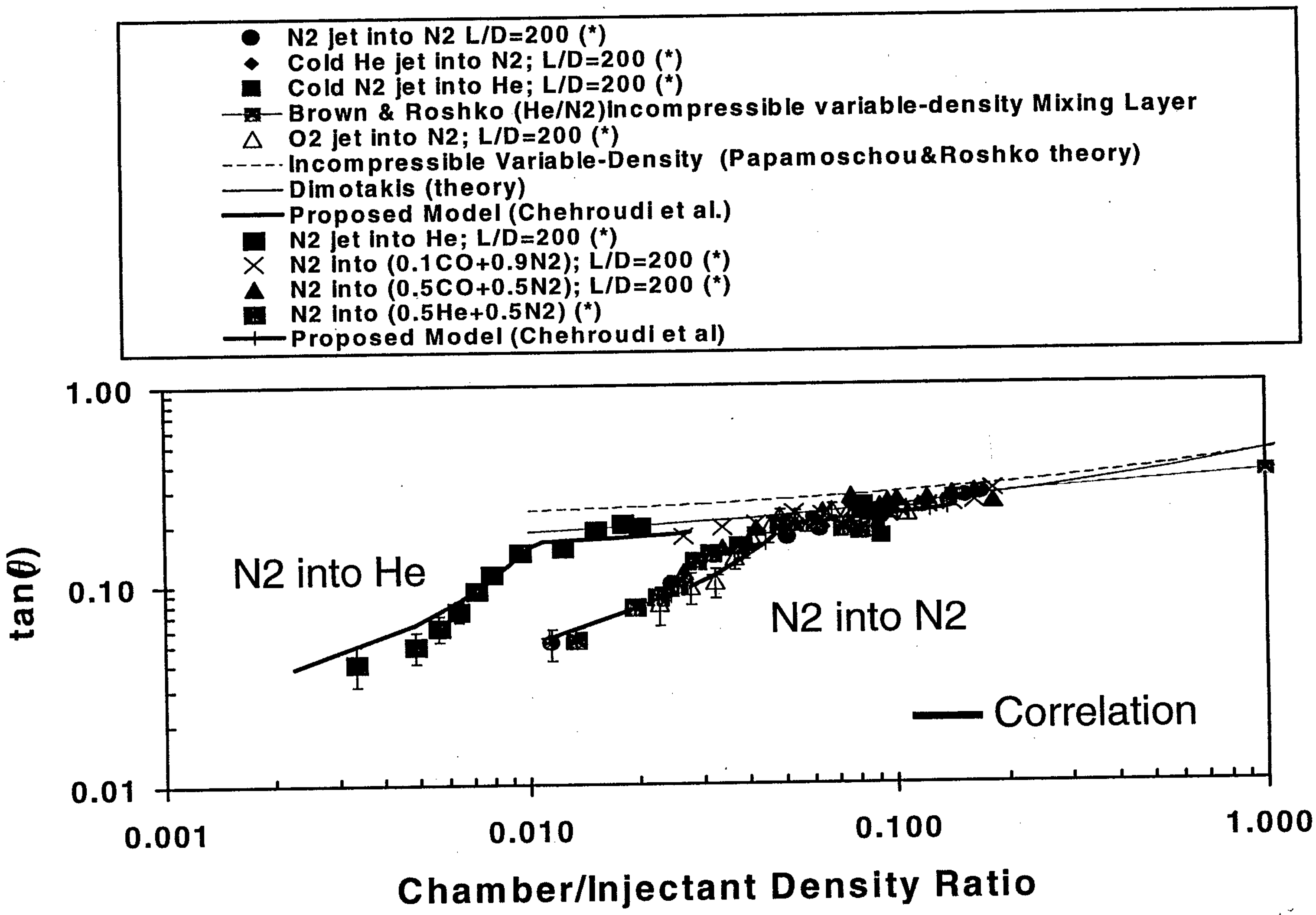
$$\theta_{Ch} \cong 0.27\ [\ G(\rho_g/\rho_l) + (\rho_g/\rho_l)^{0.5}]$$ where

$$G(\rho_R) = F(\rho_R')$$

$$\rho_R = (\rho_g/\rho_l)\ ; \qquad \rho_R' = \rho_R - (1-X)\rho_R = X\rho_R$$

X=1.0 for N_2-into-N_2; **X=0.2** for N_2-into-He ; **X=1.2** for N_2-into-Ar.

Empirical Correlation (3)



Fractal Dimension vs Reduced Pressure

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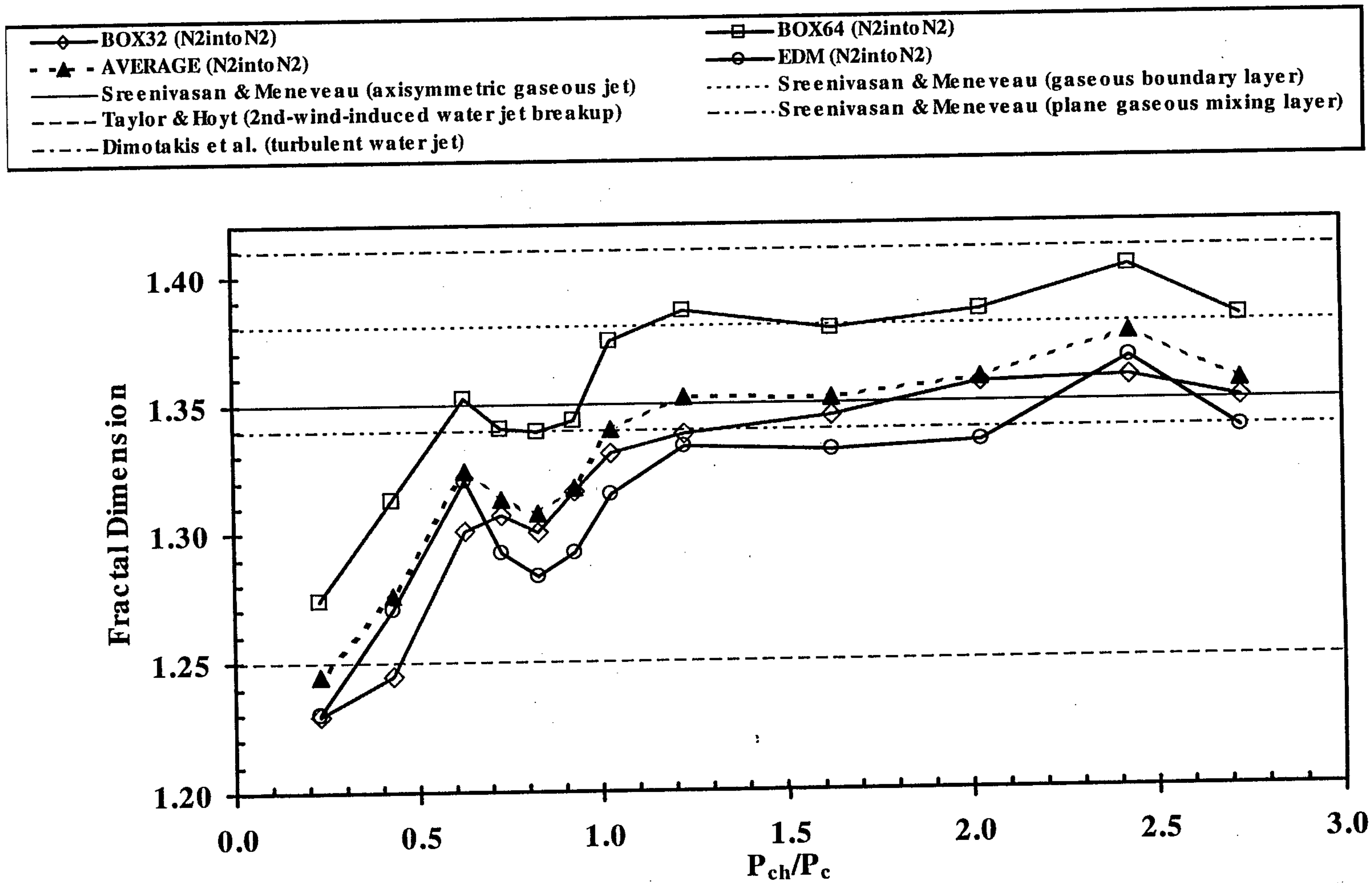
Chehroudi et. al., AIAA 99-2489



Results in Isothermal N_2 at 273 K

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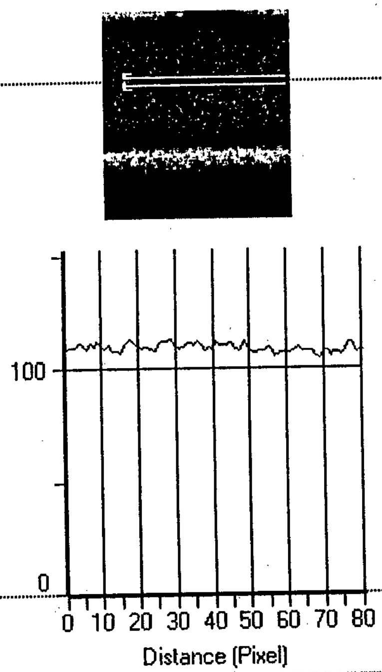
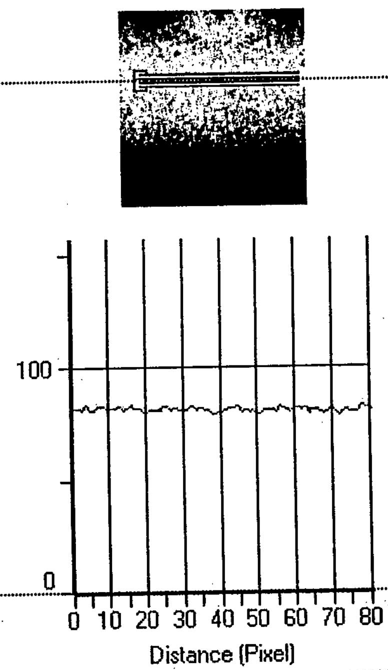
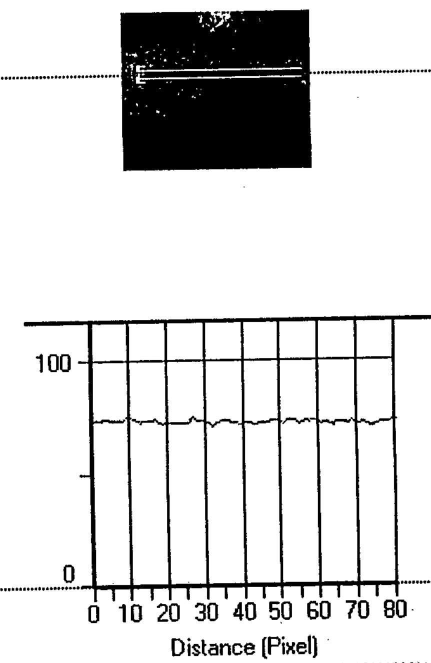
6.90 MPa (1000 psig)



2.82 MPa (400 psig)



1.46MPa (200 psig)



Chamber Pressure Mpa	Density Ratio Based on P-Measurement & Ideal Gas Nitrogen	Dark-background-corrected Camera-measured Intensity Ratio Nitrogen
6.90	4.73	4.78
2.82	1.93	1.89
1.46	1.00	1.00

2-D Raman Images, N_2 into N_2

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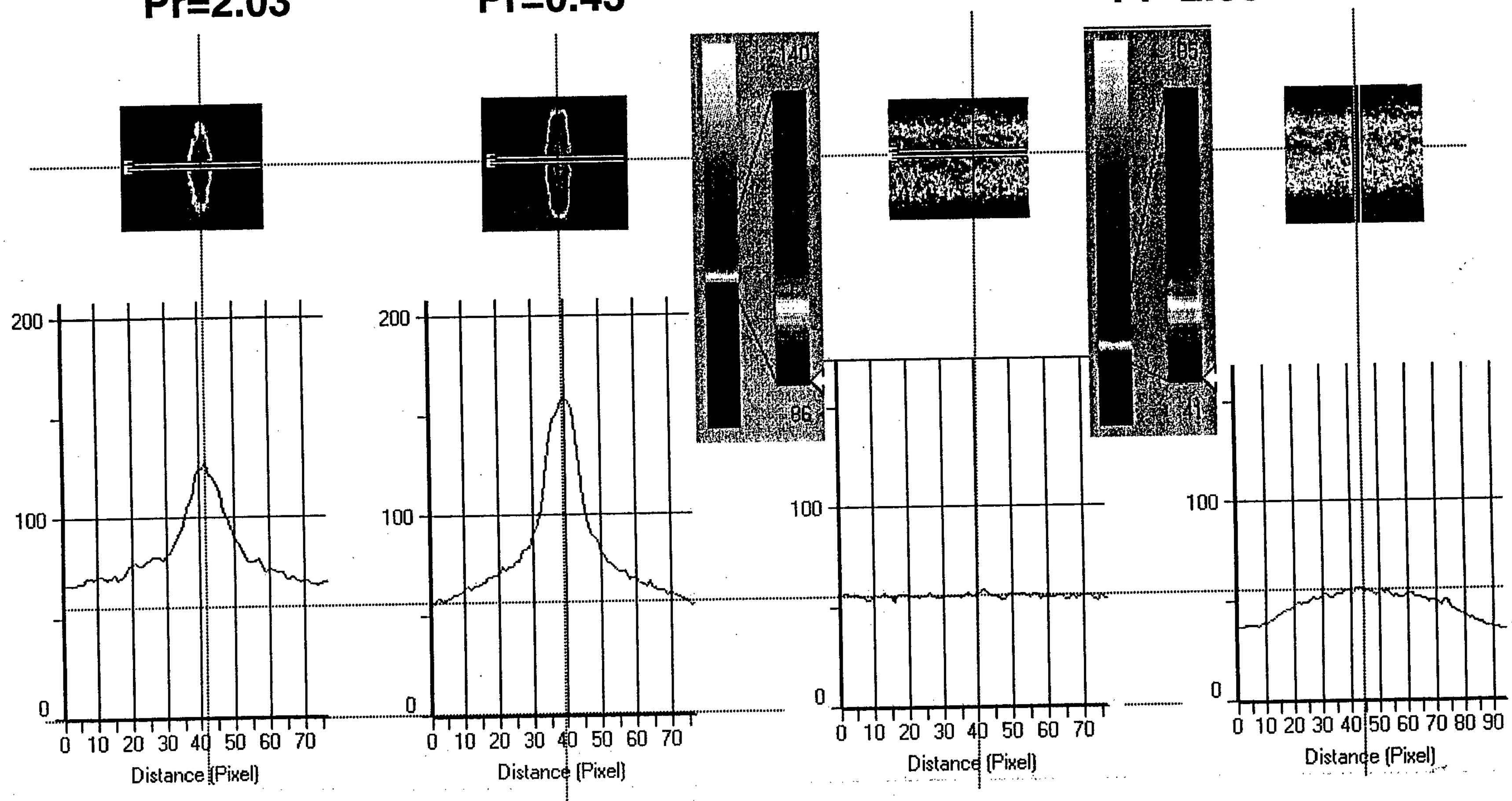
Re= 12,000 to 35,000; X/D = 2.44; sheet center



Intensity Defect vs Normalized Radius

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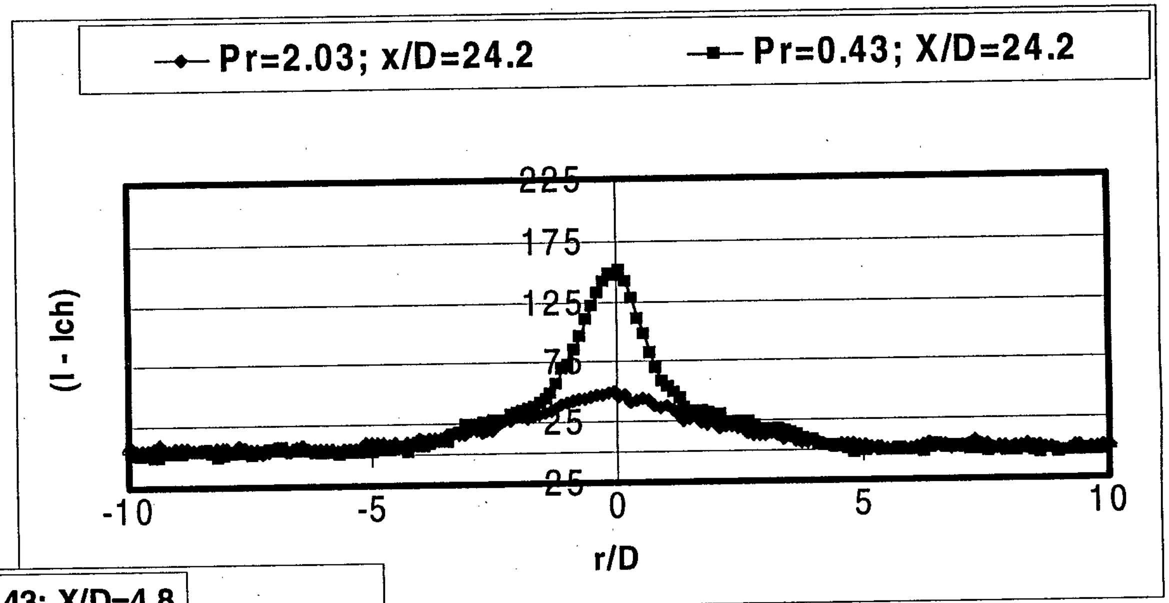
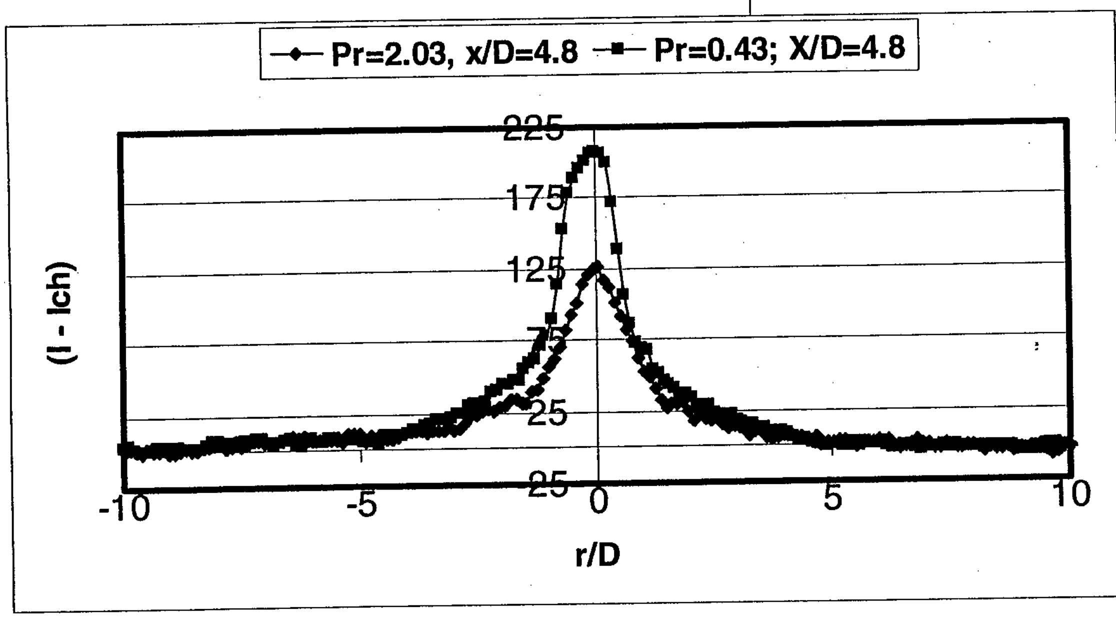
N_2 into N_2





Normalized Intensity Defect Plot: Reference Case

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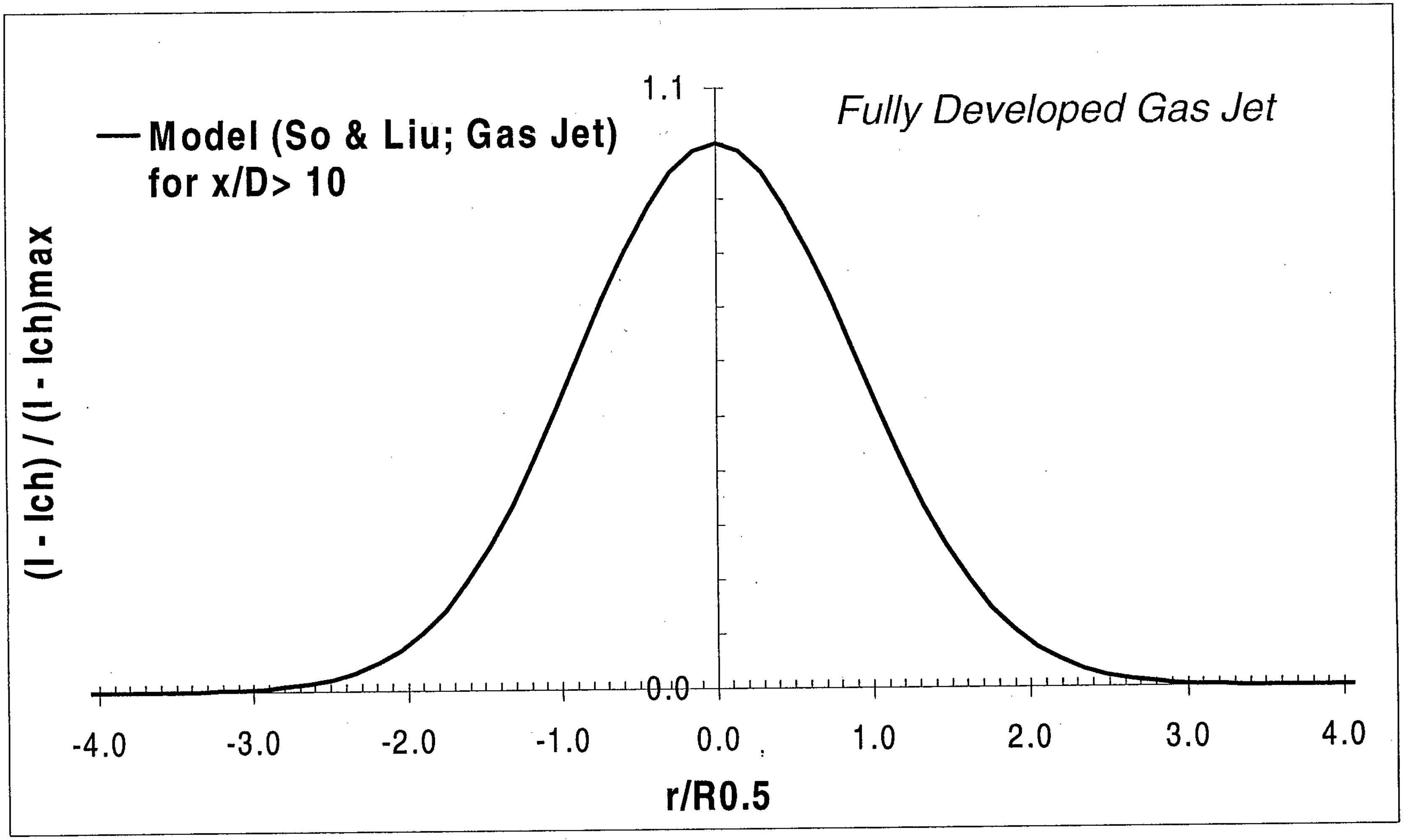

Normalized Intensity Defect Plot: Supercritical Regime

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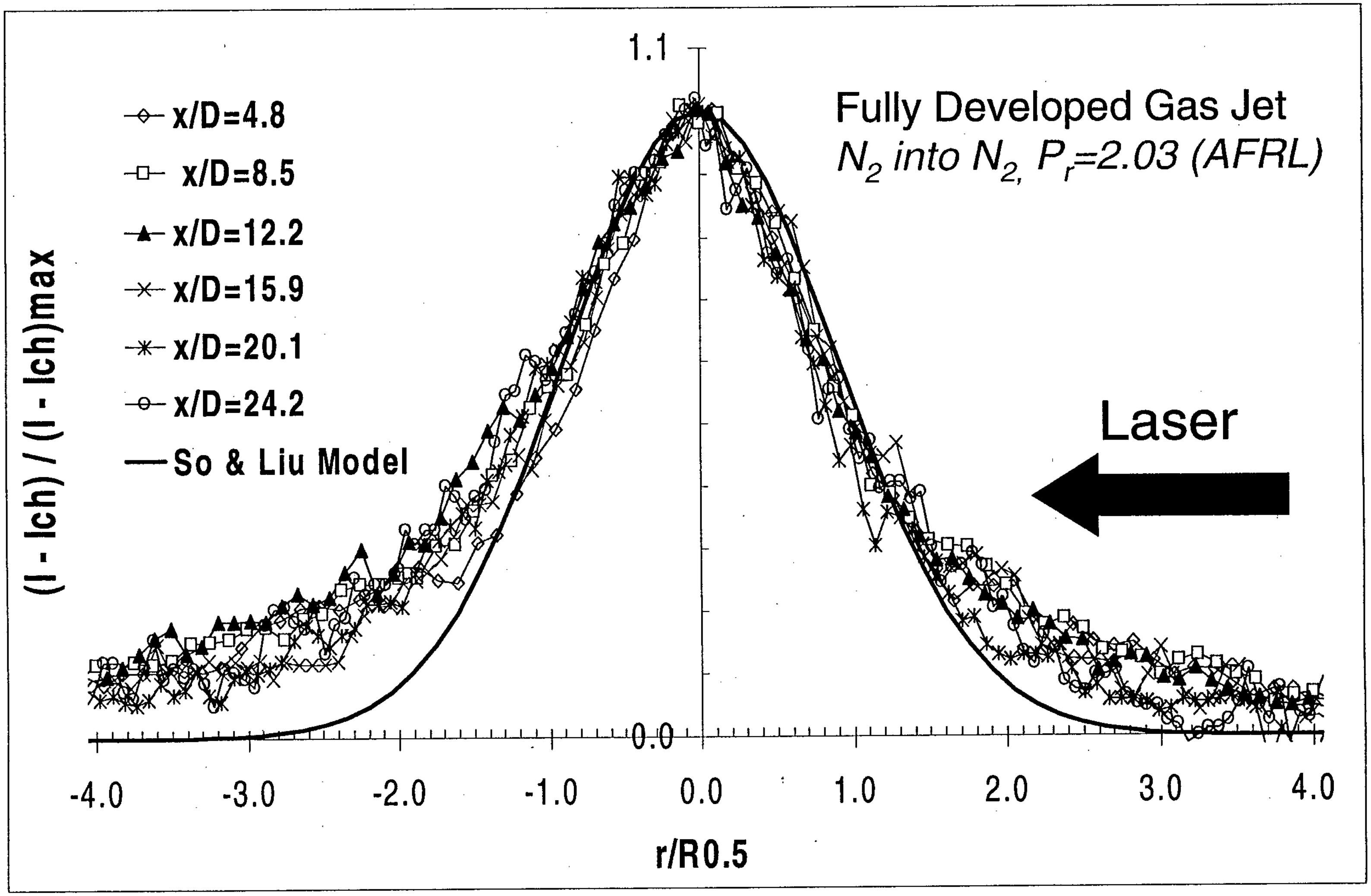

Normalized Intensity Defect Plot: Supercritical Regime (3)

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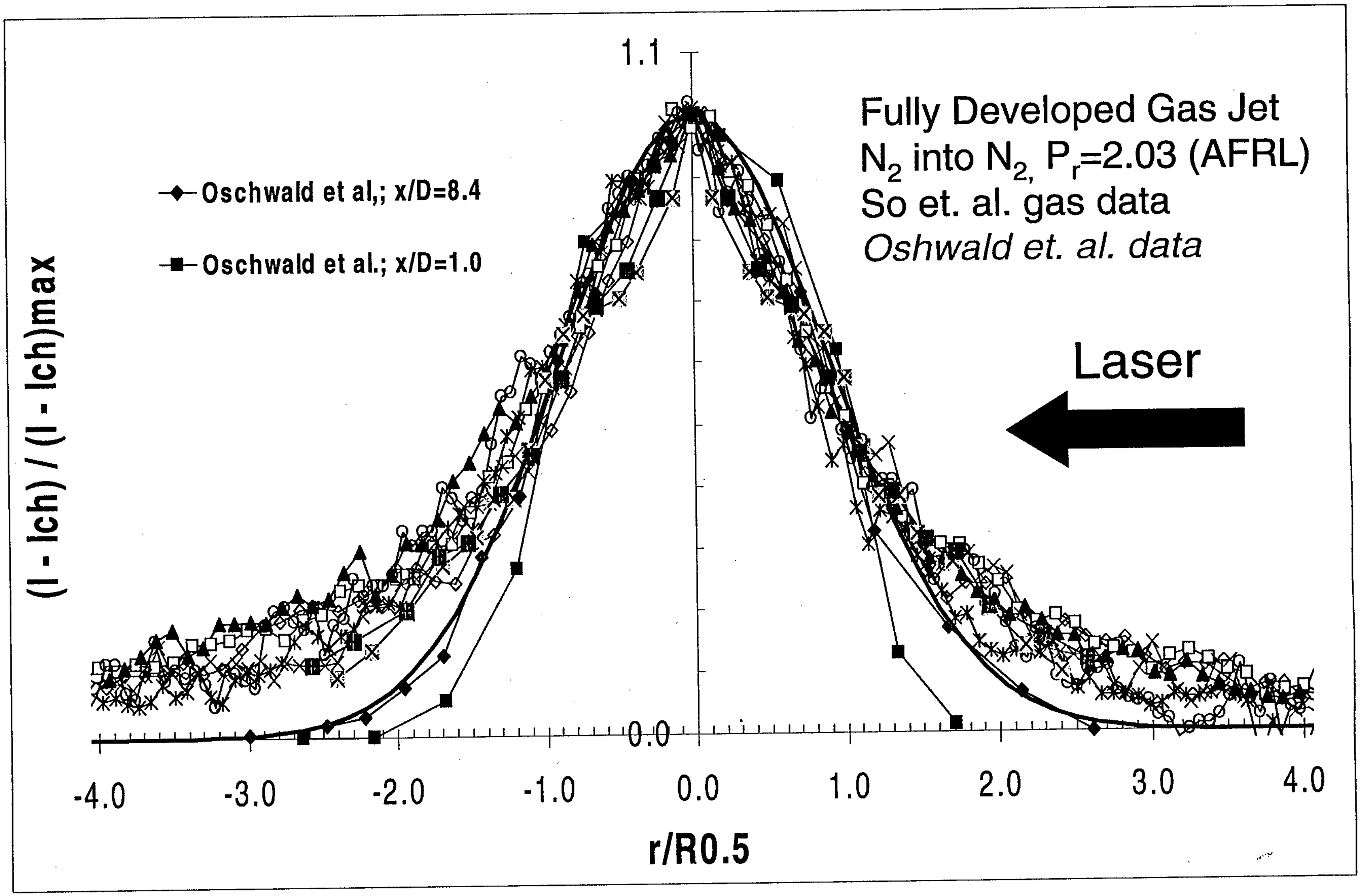

Normalized Intensity Defect Plot: Supercritical Regime (4)

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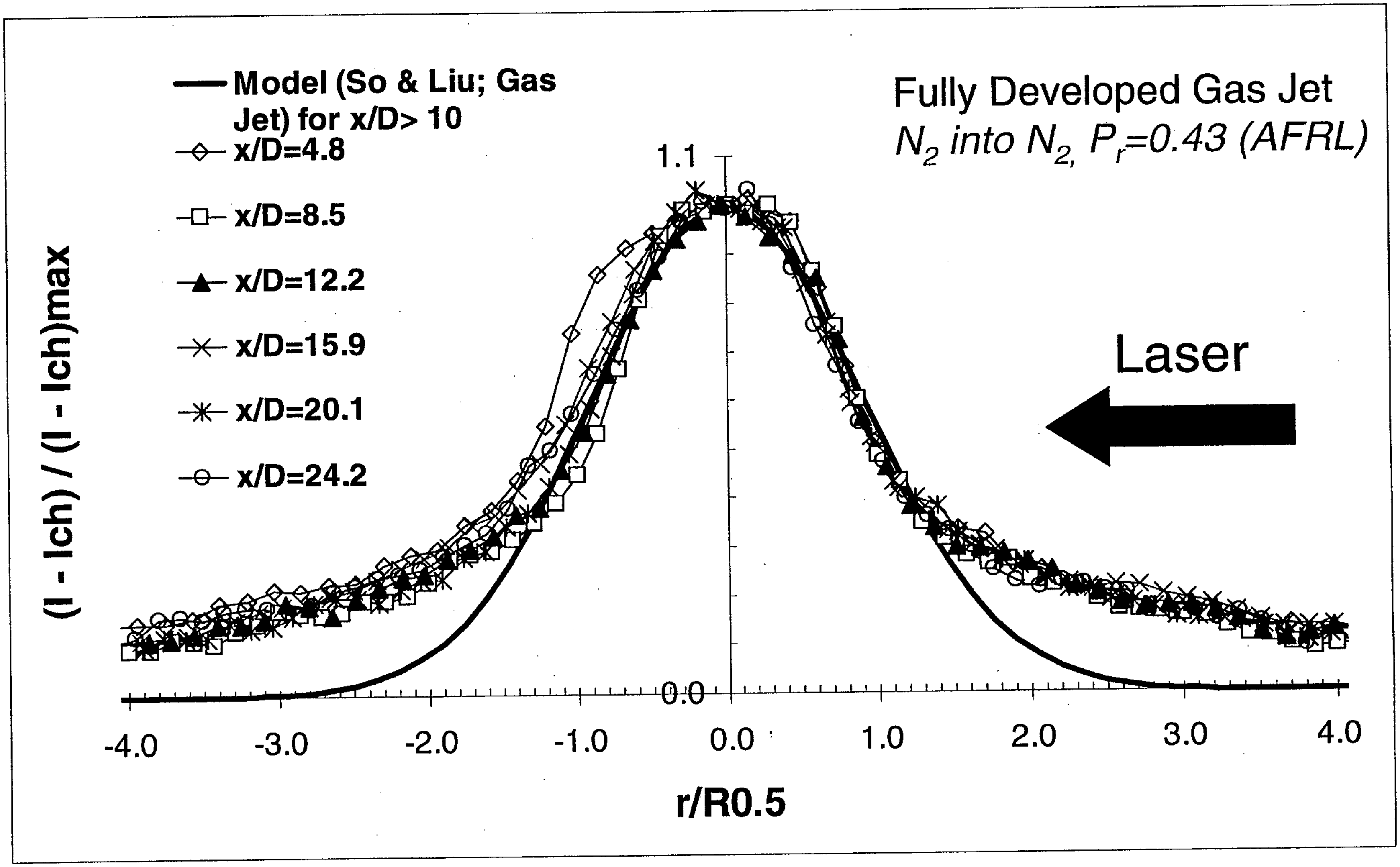
	X/D	Pch	Pr	Inj. Temp	Inj. Vel	Re	Inj/Cham
		MPa		K	m/s		density ratio
Oschwald et al.	1.0	4.0	1.2	140	5.0	115000	3.3
Oschwald et al.	8.4	4.0	1.2	118	5.0	126000	12.5
Chehroudi et al.	4.8 to 24.4	6.9	2.0	95	8.0	35000	7.1
Chehroudi et al.	4.8 to 24.4	1.5	0.4	110	8.0	12000	40.6
So et. al.	5.1	0.1	--	275	11.6	5000	0.6
So et. al.	6.4	0.1	--	275	11.6	5000	0.6

Normalized Intensity Defect Plot: Subcritical Regime

AFRL



Growth Rates

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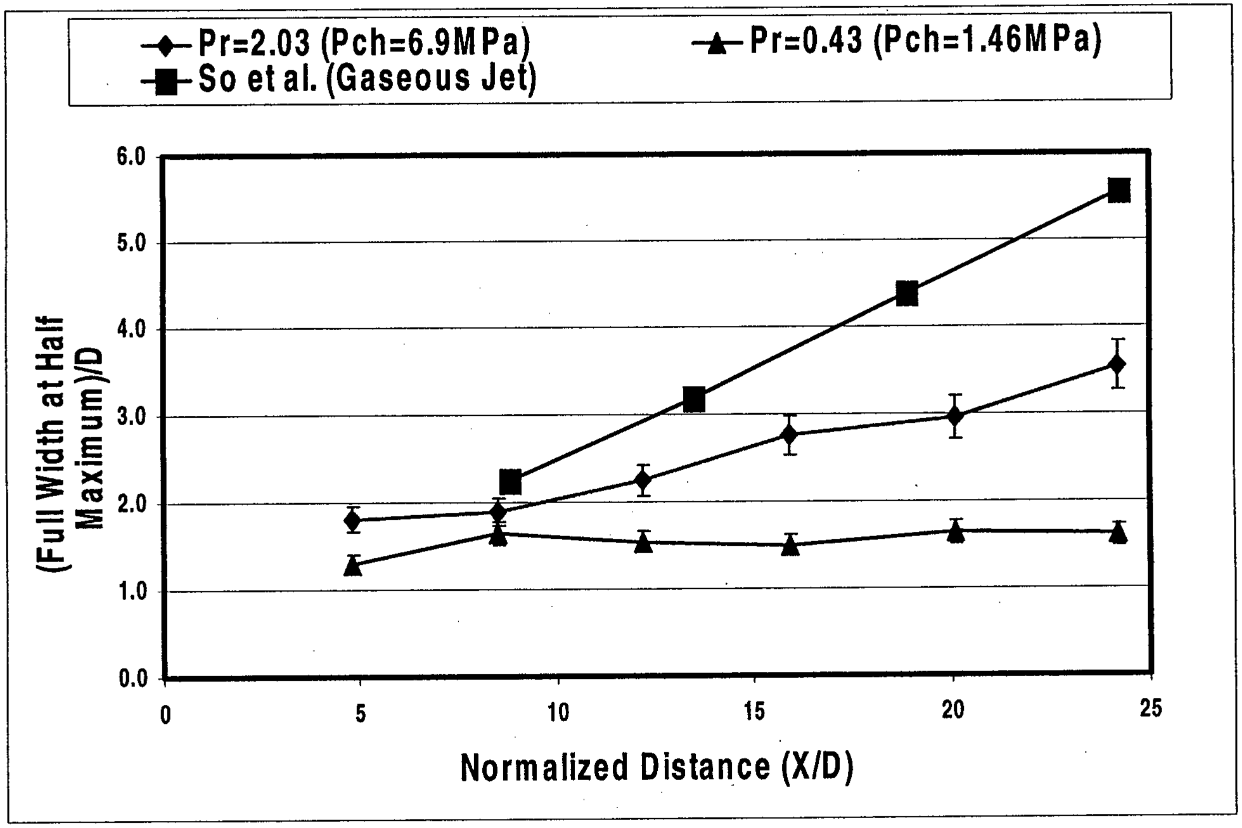

Comparison of Shadowgraph Measurements with Raman Measurements

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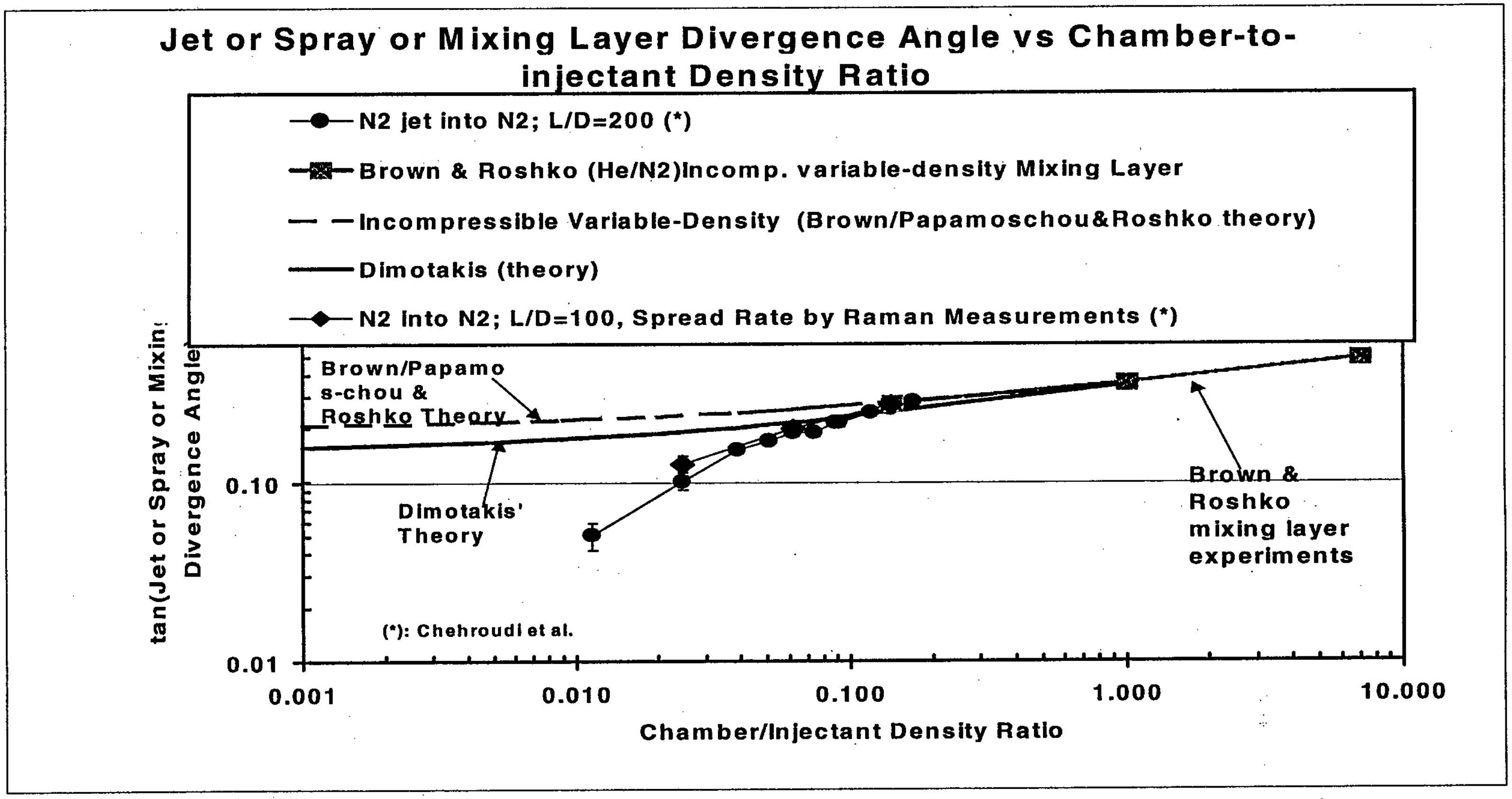

- Setting $\theta = 2$ x FWHM produces agreement with shadowgraph measurements.
  - Consistent with the observations of Brown and Roshko

Summary & Conclusions

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- Structural differences in cryogenic jets have been observed below and above the thermodynamic critical point.
- Liquid-Jet like appearance occurs up to near the critical point, similar to second wind-induced liquid jet breakup regime.
- Gas-jet like appearance occurs above the critical point. No drops are observed.
  - Supercritical spreading rate measurements agree quantitatively with incompressible variable density mixing layer experiments and theory.
  - Supercritical fractal dimensions agree quantitatively with gas jet measurements.
- New and existing mixing layer growth rate experiments and theory have for the first time been consolidated into a single plot as a function of density ratio, where the density ratio spans three orders of magnitude.
- A physical mechanism and correlation have been proposed to describe the transition from spray to gas jet behavior.

Summary & Conclusions (Raman)

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- Measurement system integrity has been established by performing Raman measurements of isothermal N_2 at different pressures.
- Measurements were constrained to the near-field in order to maintain large Froude numbers (minimize buoyancy).
- Growth rates measured from Raman profiles measured at 2 x FWHM point agree well with shadowgraph measurements.
  - The equivalency of visual and density growth rates has also been reported in the literature (Brown & Roshko, 1974).
- To within experimental error, the near-field plots appear to reduce to self-similar shapes for both the supercritical and subcritical cases.
  - Not the same profile as for fully developed turbulent gas jets.
- The near-field supercritical profile more closely approaches that of fully developed turbulent gas jets than the near-field subcritical profile.

Future

- Complete N_2-into-N_2 analysis.
- Reduce and analyzise N_2-into-N_2/He data.
- Acoustic experiments.